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Mechanics and Stability of the Lookout Creek Earth Flow

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ABSTRACT

The Lookout Creek earth flow in the western Cascade Mountains of Oregon has moved an average of about 3.5 in. (8.9 cm) annually over the past decade. The currently active slide mass which has been moving for at least the past 80 years, overlies a 40,000-yr-old debris deposit. Monitored since 1975, measurable earth flow movement occurs only during the wet season; piezometric level, which is at or near the ground surface, varies only about 3 ft (0.9 m) between the wet and dry seasons. The base of the earth flow appears to be a shear zone about 10 in. (25 cm) thick located at a depth of 21.5 ft (6.5 m). Although earth flow movement does not correlate directly with piezometric levels, it does correlate with shear-zone pore-water pressures computed with a finite-difference approximation to the Terzaghi theory of one-dimensional consolidation; the finite-difference model uses piezometric pressure measured in the earth flow as a boundary condition. A rise in pore-water pressure in the shear zone of about 85 psf (4.1 kPa), or 1.4 ft (0.4 m) of water, is the calculated threshold value at which the earth flow begins to move. However, because the earth flow has a high drainage capacity, timber harvesting, which affects the ground-water regime, is unlikely to induce a large increase in movement.

INTRODUCTION

Persistent mass movements, most of which have been classified as earth flows by the Varnes (1978) classification system, are a major contributor to development of the predominant landform in the western Cascade Mountains of Oregon and Washington (Swanson and Swanston, 1977). The western Cascade Mountains contain some of the most productive Douglas-fir forests in the nation, which are managed for timber by private industry and federal governmental agencies (USDA Forest Service and USDI Bureau of Land Management). However, there is concern that timber harvesting activities can accelerate movement of existing earth flows or perhaps

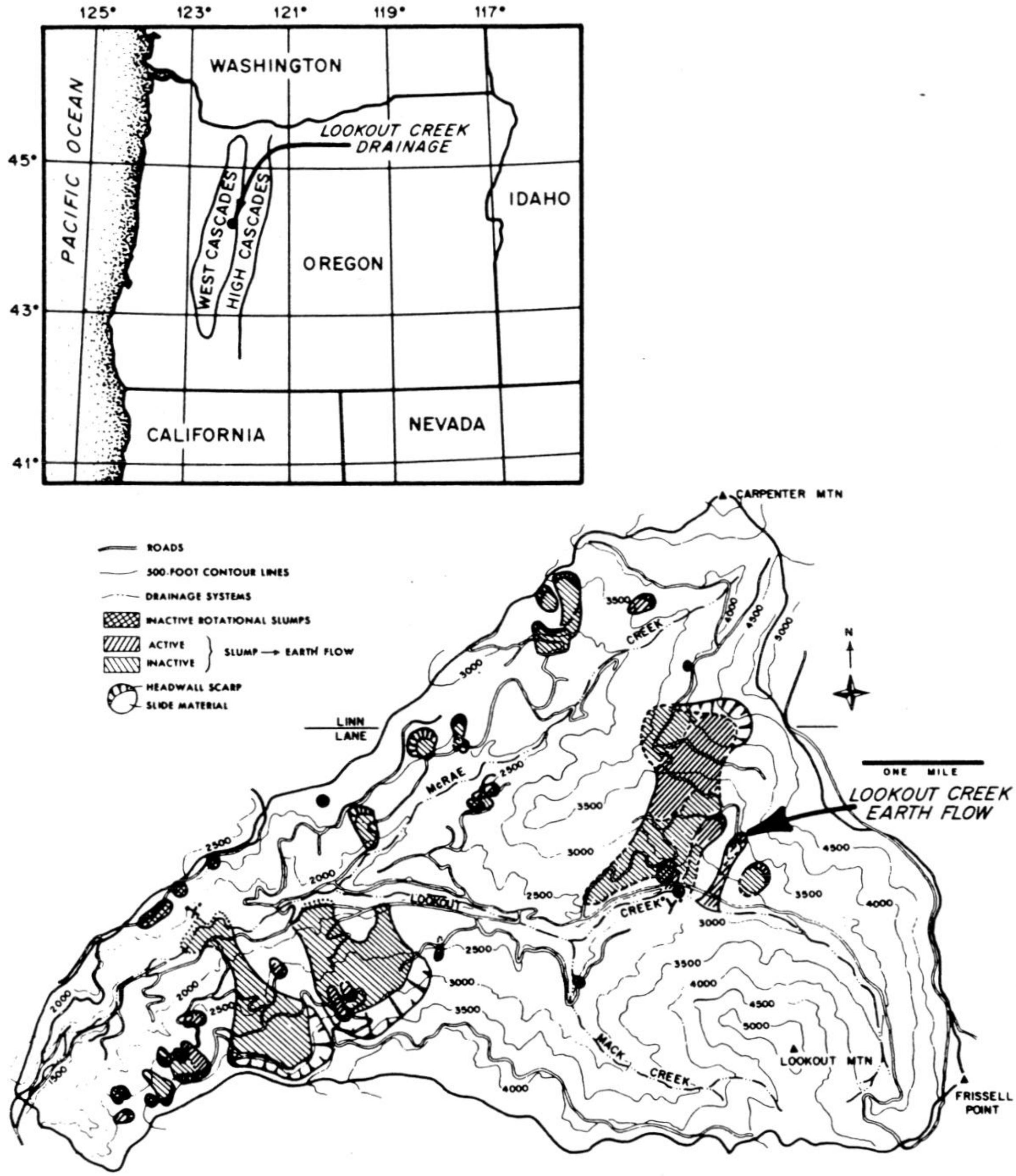

Figure 1. Location map for the Lookout Creek earth flow (adapted from Swanson and James, 1975).

trigger new ones. If a logging road intersects an earth flow, significant effort and expense may be required to maintain that road; such maintenance expenses can dramatically affect the economics of forest management. Earth flows intersecting streams can greatly increase the quantity of organic and inorganic debris in the channel locally and for some distance downstream; there is concern that this debris may adversely impact the aquatic and riparian habitat vital to water quality, fisheries, and the esthetic appeal of the stream. Thus, understanding earth flow mechanics in general, and the specific conditions leading to movement of any one earth flow, can be an important part of economic and environmental forest management.

In this paper, we examine the mechanics of an earth flow in the western Cascade Mountains of Oregon and assess what effect, if any, timber harvesting might have on its stability.

LOCATION AND REGIONAL GEOLOGY

The Lookout Creek earth flow is located along the north bank of Lookout Creek in the H. J. Andrews Experimental Forest, about 45 mi (72 km) east of Eugene, Oregon, in the Cascade Mountains (Figure 1). The Cascade Mountains of Oregon, chiefly volcanic in origin and of Cenozoic age, have two major geologic provinces, the Western Cascades and the High Cascades. The Western Cascades are older, of late Eocene to late Miocene age, and maturely dissected, consisting of deformed, partially altered lava flows and pyroclastic rock formations. The High Cascades are predominantly undeformed, unaltered andesitic and basaltic flows of Pliocene to Recent age (Peck et al., 1964).

The Lookout Creek drainage is located in the West Cascades province. The oldest exposed rocks in the drainage are in the Little Butte Formation, of Oligocene to lower Miocene age; this formation comprises massive, green, blocky breccias probably derived from mudflows and pyroclastic flows (Swanson and James, 1975). Above the Little Butte Formation, which is generally not found above elevation 2,500 ft (760 m), is the Sardine Formation, of middle to late Miocene age, 3,000 to 10,000 ft (900–3,000 m) thick and composed of a series of lava flows 10 to 100 ft (3–30 m) thick with pyroclastic interbeds. The Sardine Formation underlies the earth flow, but the upper and lower contacts of the formation near the earth flow are not well known. The uppermost rocks in the Lookout Creek drainage are andesitic and basaltic lava flows, cinder beds, and sediments overlying the Sardine Formation; these "Pliocascade" volcanics (Swanson and James, 1975) cap the ridges forming the south and east divides of the drainage.

The Lookout Creek earth flow is situated near the lower east margin of an area of complex landslide topography encompassing about 1.5 mi^2 (3.9 km^2) (Figure 1). Although the earth flow has not been dated, wood fragments excavated from the toe of a landslide of similar size about 6 mi (9.6 km) downstream were radiocarbon dated at 35,000 years before present. Mazama ash deposits on several earth flows in the Lookout Creek drainage suggest that the hummocky landscapes are at least 6,700 years old. Discontinuous glacial deposits probably of Wisconsin age (Swanson and James, 1975) are exposed along Lookout Creek as far as 2 mi (3.2 km) downstream of the earth flow. A poorly sorted gravel deposit, age unknown, which may be glacial till, lies a few thousand feet west of the Lookout Creek earth flow in the scarp of another earth flow about 250 ft (75 m) above the current level of Lookout Creek.

EARTH FLOW DESCRIPTION

The topographic expression of the Lookout Creek earth flow extends from the north bank of Lookout Creek upslope for about 2,900 ft (885 m), but the currently active area, 300 to 800 ft (90–240 m) wide, includes only the lower 1,600 ft (490 m) (Figure 2). Average ground slope of the earth flow is about 9°, but the ground surface is uneven and is locally as steep as 30°. The toe of the earth flow impinges on Lookout Creek, which appears to have been displaced to the south along the toe.

A complex shear zone bounds the west side of the earth flow. What appears to be the outermost shear crack is not active along the entire earth flow; the currently active shear crack occupies a 2 to 15 ft (0.6 to 4.5 m) deep depression. The tension crack defining the upslope (north) boundary of the active area is most distinct near the west side of the earth flow; little or no surface cracking is evident on the east side. Much of the east side extends through a series of poorly drained depressions, whose softer surface soils and vegetation obscure the shear zone. Within the active area, at least one distinct block is surrounded by surficial cracking.

The area immediately upslope of the active earth flow mass shows signs of past earth-flow-type movement. The earth flow lies at the base of a steep-faced basalt outcrop that has been referred to as the headscarp of the earth flow (Swanson and Swanston, 1977). Much of the earth flow surface is littered with boulders and cobbles probably originating from that outcrop. The association between the headscarp and the original earth flow movement is not clear, but current movement appears unconnected with the headscarp.

Surface drainage on the earth flow is discontinuous. In several sets of parallel, intermittent streams, water may flow for a hundred feet, disappear, and reappear farther down the earth flow in the same or a parallel channel. Seeps and springs abound, especially along the north boundary of the active area. Closed depressions are distributed throughout the moving mass; the largest covering 0.7 acre (0.28 ha) and ponding water 3 ft (0.9 m) deep.

The Lookout Creek drainage supports a dense coniferous forest that includes Douglas-fir, western

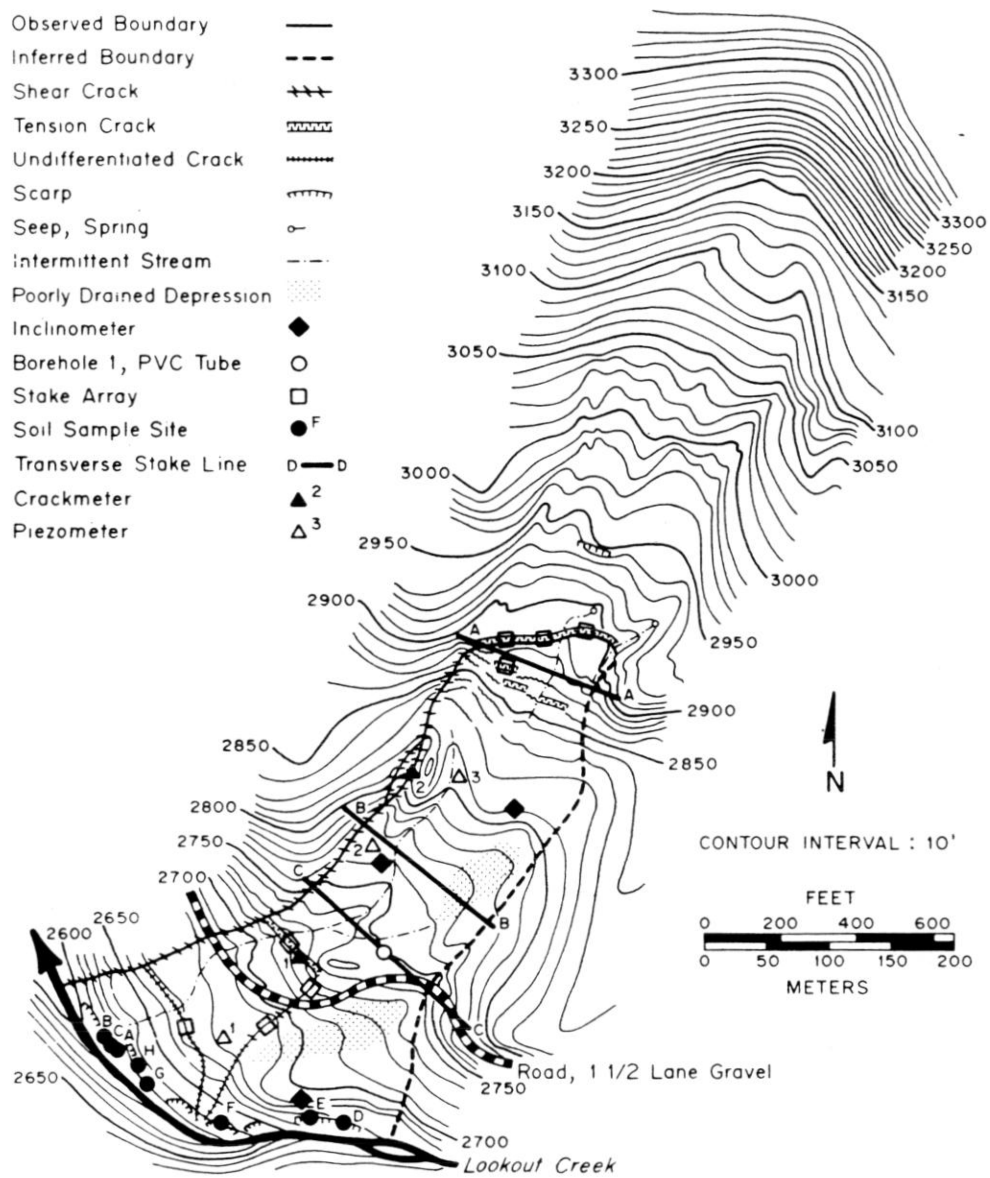

Figure 2. Topographic map of the Lookout Creek earth flow.

redcedar, western hemlock, mountain hemlock, grand fir, and noble fir. Understory vegetation ranges from vine maple and Pacific rhododendron over much of the area to devilsclub and willow in the poorly drained depressions. The distribution, size, and age of these species on and around the earth flow are influenced by ground movement, related changes in ground water, fire history, and forest management activities. Forest fires burned over the region in the mid-1800's, but many of the older trees survived and show fire scars. The survivors are mainly Douglas-fir and western redcedar, now 300 to 500 years old; most of those on the active area of the earth flow are leaning, and many have fallen over. About 3.5 acres (1.4 ha) on the east margin of the active area are part of a 25-acre (10 ha) tract that was clearcut logged in 1961. This tract is now heavily reforested by Douglas-fir and western hemlock up to 25 ft (7.5 m) tall. A forest access road crosses the earth flow at about the lower third point of the active area (Figure 2); the road, 20 to 30 ft (6–9 m) wide, was constructed with modest cuts and fills of up to 10 ft (3 m) before the 1961 clearcut.

In December, 1983, a wire-line core drill was used to drill an exploratory borehole on the earth flow (borehole 1, Figure 2). No bedrock was encountered to a depth of 151 ft (46 m) (Figure 3). Generally, the subsurface material was gravelly to bouldery with a fine-grained matrix. The incidence and apparent size of the boulders increased with depth, and a number of shifts from brown to gray matrix soil were observed. The bottom of the boring is between 20 and 50 ft (6–15 m) below the present elevation of Lookout Creek. At a depth of 120 ft (36.6 m), roughly the present elevation of Lookout Creek, a layer of rounded gravel and small cobbles interpreted to be of alluvial origin was encountered. At a depth of about 78 ft (24 m), a wood fragment was recovered in the core barrel and has been radiocarbon dated as older than 40,000 years before present.

EARTH FLOW MONITORING AND MOVEMENT HISTORY

Some movement history of the Lookout Creek earth flow can be interpreted from tree growth. At several locations near the west side of the earth flow, the trunks of standing trees have been split by either shear or tension cracks in the earth flow. The age of scar tissue in the cracks indicates that splitting, hence the associated earth flow movement, has been going on for at least 80 years (Swanson and Swanston, 1977). Moreover, some movement predates the currently standing old-growth Douglas-fir and western redcedar trees on the earth flow, although it is uncertain whether this ancient movement was of the same pattern observed today.

Movement of the Lookout Creek earth flow was first monitored in the 1975 water year (WY) (Oct. 1, 1974–Sept. 30, 1975) with stake arrays installed across shear and tension cracks at the boundary of the active area and across tension cracks within it. These stake arrays were originally surveyed twice a year, but the frequency was increased to about every 3 weeks in 1977 to determine the amount and distribution of annual movement. Also, in 1977, recording extensiometers, each consisting of a steel tape linked to a drum chart recorder, were installed across the shear crack along the west side of the active area and across a tension crack within it (Figure 2) to continuously monitor movement. Diurnal temperature fluctuations and the sensitivity of the drum chart drive make accurate readings of daily movements possible only at velocities greater than about .02 in./day (.50 mm/day). Thus, the best extensiometer record gives only 3- to 5-day averages of daily movement.

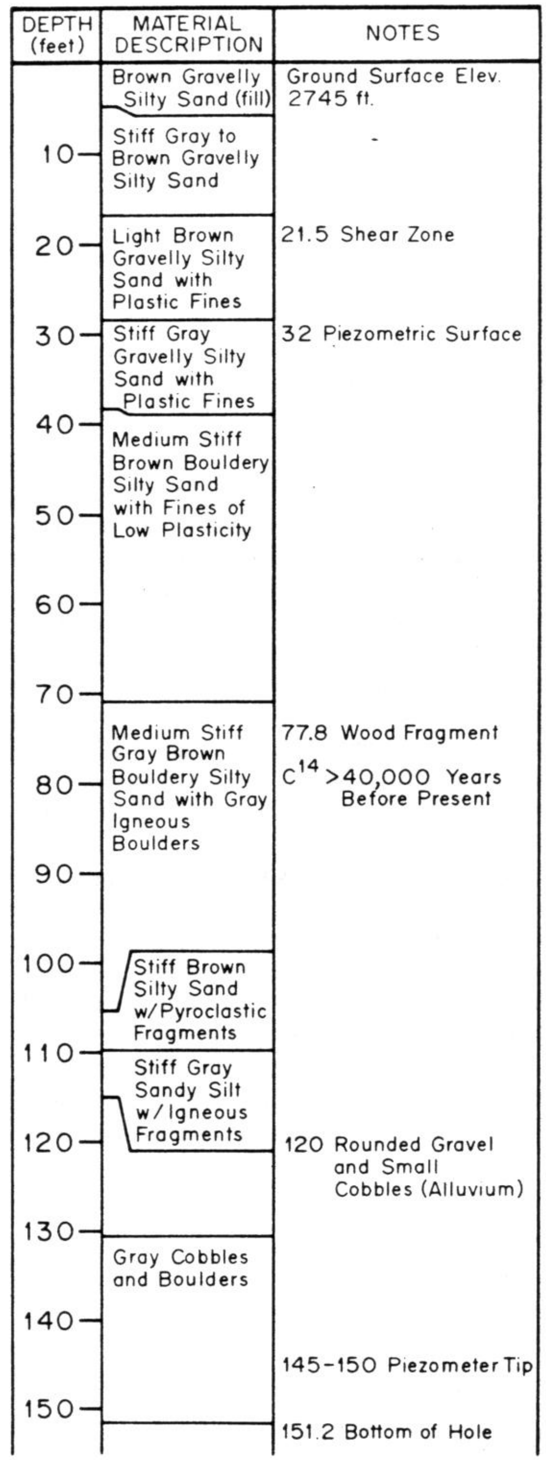

Figure 3. Boring log of borehole 1, transverse stake line C, of the Lookout Creek earth flow.

Movement of the Lookout Creek earth flow is seasonal, corresponding with the increased rainfall

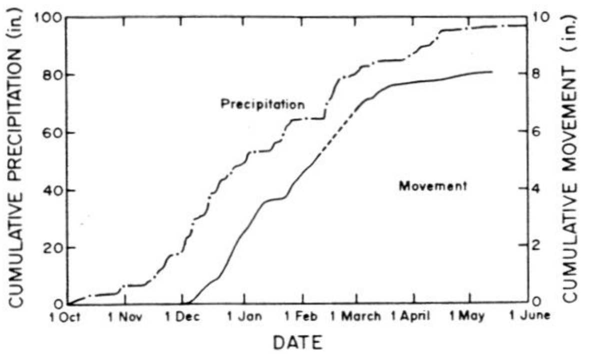

Figure 4. Typical annual pattern of cumulative precipitation and movement for the Lookout Creek earth flow (WY 1982).

beginning in September and October and continuing until April or May (Figure 4). Swanson and Swanston (1977) found that movement over 1- to 4-month periods in 1975–76 correlated with precipitation. However, annual movement does not correlate consistently with wet-season rainfall (Figure 5); in WY's 1982 and 1983, wet-season rainfall was nearly the same, but annual earth flow movement in 1982 (8.15 in. (20.7 cm)) was over three times that in 1983 (2.6 in. (6.6 cm)); precipitation in WY 1979 was 20 percent less than in WY 1978, but annual movement was 75 percent greater.

Three inclinometer casings also were installed 17 to 25 ft (5.2–7.6 m) deep in the earth flow in the mid-1970's. The inclinometers measured only a few hundredths of an inch total deformation per year, distributed evenly with depth. However, these small deformations do not correspond with surface movements in the same area, indicating that the inclinometer casings did not penetrate the seat of movement. Yet the measurements show that the

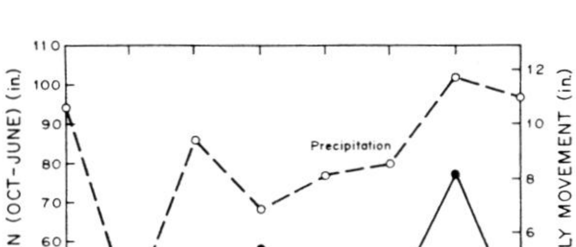

Figure 5. Annual movement and wet season precipitation for the Lookout Creek earth flow, WY's 1976–83.

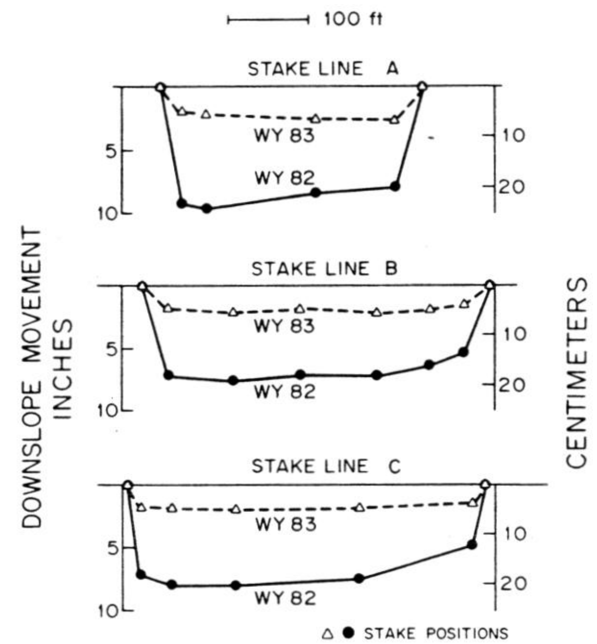

Figure 6. Downslope movement at transverse stake lines A, B, and C of the Lookout Creek earth flow for WY's 1982 and 1983.

movement pattern is not one of surficial creep; therefore a shear zone or zones should be expected at some depth below the inclinometers.

In 1981, transverse stake lines A, B, and C were established on section lines across the earth flow to better define the east margin and determine how local movement varies from the lower to upper portion of the active area (Figure 2). During WY's 1982 and 1983, the west margin moved slightly faster per year than the east margin, but the movements generally were of the same order (Figure 6). Continuity computations assuming no compression or extension of the earth flow mass indicate that the earth flow thickness is relatively constant from transverse stake line A to stake line C. A 1-in. (2.54 cm) PVC tube was installed to a depth of 151 ft (46 m) in borehole 1 drilled on stake line C so that depth to the seat of movement and the shear zone thickness could be estimated. For the purpose used here, the shear zone thickness will be defined as the actual shear surface and that soil above and below the shear surface that is significantly softer than the gravelly material above and below the shear zone.

By the end of WY 1983, 2.15 in. (5.4 cm) of surface movement had been measured at the borehole. At this time, a rod 4 in. (10.1 cm) long and 0.5 in. (1.27 cm) in diameter would pass to the bottom of the PVC tube without encountering re-

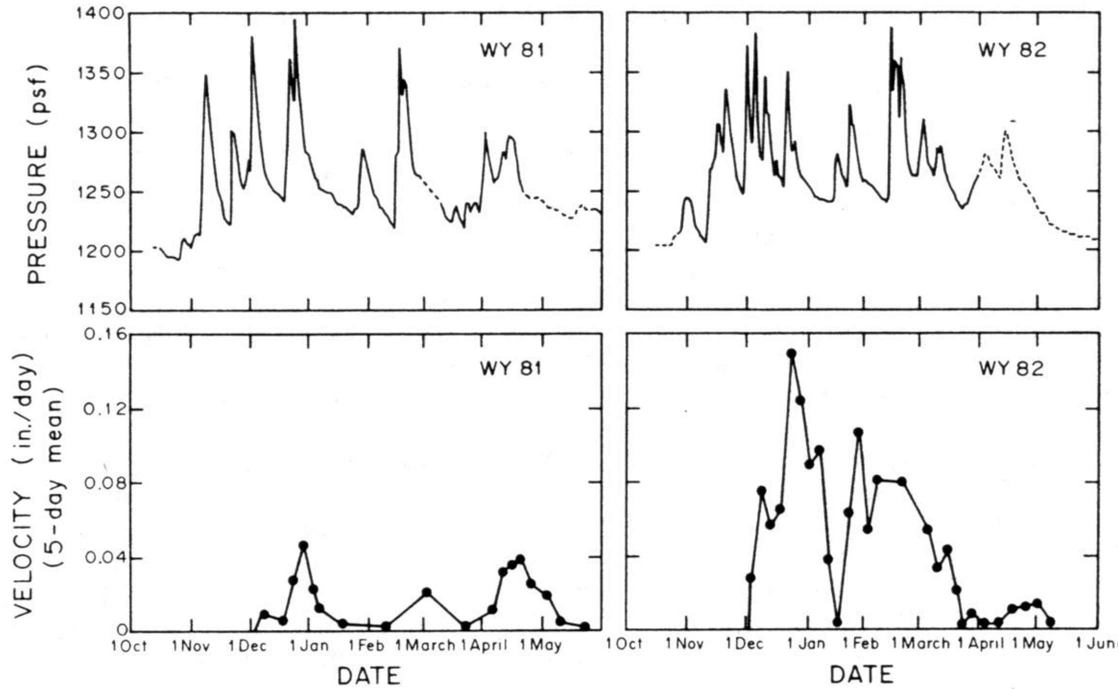

Figure 7. Daily pore-water pressures on the upper boundary of the shear zone obtained from piezometer readings within the Lookout Creek earth flow, and velocity (5-day mean) of the earth flow, WY'S 1981 and 1982.

sistance, but an equal diameter rod 10 in. (25.4 cm) long would only pass to a depth of 21.5 ft (6.55 m), indicating a shear zone. If the PVC tube is assumed to deform across the shear zone in a symmetric reverse curve, and if the maximum length rod which can pass that curve is 4 to 10 in. (10.1–25.4 cm) long, geometric computations show that the vertical distance along the reverse curve would range from 6.5 to 12.1 in. (16.5–30.7 cm). Generally, these values would be an upper estimate of shear-zone thickness because the stiffness of the PVC tube would require it to bend over a longer length than the actual thickness of the shear zone. However, the material in the earth flow and below the shear zone (as indicated by disturbed samples taken from the borehole) should be significantly stiffer than the PVC tube, hence the reverse-curve computations should closely estimate the shear zone thickness.

Beginning in 1976, continuously recording piezometers were installed in the earth flow (Figure 2), their tips 10 to 15 ft (3–4.5 m) below the ground surface (above the shear zone), in the hope that piezometer and extensiometer data would correlate and help explain the timing of earth flow movement (Figure 7). Water level in piezometer 1, near the toe of the active area, has been monitored continuously during the wet season since its installation. However, the other piezometer records were not maintained continuously when it became apparent that piezometer 2 mirrored the response of piezometer 1, and piezometer 3 mirrored the water level of a nearby sag pond.

A fourth piezometer was installed in borehole 1 (Figure 2) with the tip at a depth of 145 ft (44 m) (well below the shear zone subsequently found in borehole 1). Periodic monitoring of this piezometer during WY 1983 showed that the piezometric surface was generally about 32 ft (9.75 m) below the ground surface, far below the level indicated by the other piezometers and a sag pond immediately adjacent to borehole 1; this suggested a water table at or near the ground surface, with ground water perched in the earth flow, possibly on top of the shear zone.

STABILITY AND MECHANICS OF MOVEMENT

The active area starts to move every fall and, in an average rainfall year, stops moving in the spring, though movement may slow or stop several times during the wet season. In classical terms, the factor of safety of the earth flow with respect to limit equilibrium ≥ 1.0 before movement begins in the fall, is ≤ 1.0 during movement, and increases to a value >1.0 when movement stops in the spring.

A quantitative study of earth flow stability requires data on both soil properties and pore-water pressures. Attempts to obtain undisturbed samples for testing of the shear zone were unsuccessful. A wire-line core drill was necessary to advance borehole 1 through the boulders that make up the earth flow mass and the debris deposit below the earth flow. This method, however, had the disadvantage of returning only disturbed samples of the soil matrix in which the shear zone apparently is located. Further, even if undisturbed sampling of the relatively thin shear zone had been possible, the number of borings required to obtain samples for strength testing would have been well beyond the scope and budget of this investigation. However, because the earth flow has a factor of safety ≤ 1.0 when moving, it is an ideal candidate for stability back-analysis.

Because of the great length of the Lookout Creek earth flow relative to its thickness, stability back-analysis was conducted by the infinite-slope method with the factor of safety equation for seepage parallel to the slope and cohesion equal to zero,

$$\text{F.S.} = \frac{[d\gamma - (d - d_w)\gamma_w]\tan\phi'}{d\gamma\tan\beta} \qquad \text{Eq. 1}$$

where:

F.S. = factor of safety
ϕ' = effective friction angle (degrees)
β = failure-surface, phreatic-surface, and ground-surface angle (degrees)
γ = total unit weight of soil (pcf)
γ_w = unit weight of water (pcf)
d = depth to the failure surface (ft)
d_w = depth to the phreatic surface (ft)

The factor of safety was set equal to 1.0 to reflect the existing condition of instability, and cohesion was not considered, to reflect the residual strength condition on the shear zone (Lambe and Whitman, 1969). A β-angle of 9° for the average ground slope, total unit weight of soil of 120 pcf (18.9 kN/m^3), and depth to the failure surface of 21.5 ft (6.55 m) were used in the back-analysis.

The piezometric surface in the earth flow varies from just above the ground surface, where water is ponded, to about 8 ft (2.4 m) below the ground surface at piezometer 1. During the wet season, the piezometric surface at piezometer 1 rises about 3 ft (0.9 m), and at some point in this 3-ft rise, the earth flow becomes unstable. Depth to the phreatic surface of 3 to 6 ft (.9–1.8 m) was used in the back-analysis to reflect the wet-season increases superimposed on the average depth for the earth flow.

Computed shear-zone friction angles ranged from 14.2° to 16.0° for the lowest and highest phreatic surfaces, respectively. The infinite-slope computations were checked by a two-dimensional method of slices stability analysis for a noncircular failure surface (Wright, 1974); friction angles were about 2 percent lower than those computed with the infinite-slope method.

The friction angles presented above provide a definite range in which the actual average friction angle must lie, but a detailed understanding of the mechanics of earth flow movement requires a more exact value of the friction angle and above all, a consistent picture of stability. In an effective stress back-analysis, the phreatic surface level that corresponds to a factor of safety of 1.0 is necessary for computing the actual friction angle. For drained behavior, this phreatic surface level should be the level on the day movement begins. Furthermore, the computed friction angle, as a residual friction angle, should be essentially constant from year to year, requiring that the phreatic surface level on the day that movement begins be the same from year to year. However, this was not the case; phreatic surface levels at piezometer 1 on the day movement began ranged from 5.3 to 7.2 ft (1.6–2.2 m) below the ground over the period of record, and piezometer records indicate behavior inconsistent with a factor of safety decreasing to 1.0 on that day. In some years, piezometric level on the day movement began was exceeded several times before that day and may actually have been declining.

These observations lead to the hypothesis that the shear zone soil is behaving in a partially-drained manner when the earth flow becomes unstable. Partial drainage would exist if pore-water pressures in the earth flow were not instantaneously transmitted into the shear zone. This requires a shear zone of very low permeability. Boring 1 (Figure 3) and test pits at the toe of the earth flow indicate that the earth flow and material below the earth flow for considerable depth consist of gravelly to bouldery debris with a fine grained matrix. Permeability values determined from laboratory tests on fine-grained matrix soil samples from the toe of the earth flow reveal inclusions of very impervious material within the earth flow mass (coefficient of permeability = 3×10^{-10} ft/sec; 9×10^{-9} cm/sec). Indeed, the back-calculated friction angles for the shear zone are far lower than should be expected for the gravelly to bouldery material encountered in borehole 1 (Figure 3); strong evidence that the shear zone is made up of a large lense or a series of lenses of fine-grained material. However, the overall earth flow mass has a high "formation permeability," indicated by the discontinuous surface drainage pattern. A shear zone of very low permeability is also suggested by readings from the deep peizometer (borehole 1) which indicate a piezometric surface below the base of the earth flow.

To accurately and directly determine the pore-water pressures in the shear zone would require precise placement of a piezometer tip in the shear zone. This was impractical for two reasons. First, testing the partial-drainage hypothesis would require measuring pore-water pressures at a known relative position in the shear zone. This would require placement of a small piezometer tip at a known position in the shear zone that is about 1 ft thick. Because depth to the shear zone likely varies by at least a foot or two from place to place on the earth flow, the required precision is problematic. Second, in a thin, partially-drained shear zone, disturbance from installing a piezometer would make the piezometer readings questionable.

However, a good indication of pore-water pressures can be obtained by modeling the propagation of pore-water pressures from the pervious earth flow mass through a much less pervious shear zone with the Terzaghi theory of one-dimensional consolidation (Taylor, 1948). If the hypothesis of partial drainage is correct, then the pore-water pressure computed for the shear zone when the earth flow begins to move (factor of safety = 1.0) should be the same for each year. The value of pore-water pressure that initiates movement can be termed the threshold pore-water pressure.

CONSOLIDATION-MODEL DESCRIPTION

The Terzaghi theory of consolidation relates nonequilibrium pore-water pressure (u), time (t), vertical position within a soil layer (z), and soil permeability and compressibility by the differential equation

$$\frac{\partial u}{\partial t} = c_v \frac{\partial^2 u}{\partial z^2} \qquad \text{Eq. 2}$$

where: c_v = coefficient of consolidation (includes effect of compressibility and permeability).

The classical use of the solution to this equation is to predict the rate of settlement associated with nonequilibrium pore-water pressures resulting from a ground-surface loading. However, because Equation 2 is a general equation, it can also be used to predict pore-water pressures regardless of the source if the boundary conditions are known. Equation 2 may be solved directly for a number of simple boundary conditions (Taylor, 1948), but a finite-difference approximation is the most tractable solution for complicated boundary conditions.

In the classical case, a foundation contact pressure is assumed to produce an equal nonequilibrium pore-water pressure throughout the soil layer concerned. The boundary pore-water pressures are assumed to be in equilibrium with the pore-water pressure field in the adjacent soil layer not subject to the consolidation. At an impermeable boundary, the nonequilibrium pore-water pressure gradient is assumed to be zero. The solution to Equation 2 shows that nonequilibrium pore-water pressures dissipate over time as pore water flows toward the permeable boundary.

For the Lookout Creek earth flow, the boundary pore-water pressures above the shear zone are assumed to be those indicated by the daily piezometer record from within the earth flow mass. The exact nature of the lower shear-zone boundary is debatable; thus, two conditions were considered in order to cover the range of likely possibilities. First, the lower boundary was assumed to be impermeable, to simulate the presence of material below the shear zone that is 1 to 2 orders of magnitude less permeable than the shear zone material. This condition could arise if there were a thin zone of oriented particles in the shear zone similar to those observed for other landslides (Morgenstern and Tchalenko, 1967). Because we do not know where such a thin zone might be, an impermeable boundary was considered at the bottom of the shear zone interpreted from the bore hole displacement (Case 1a, Table 1), and also at the center of the shear zone (Case 1b, Table 1). Second, the lower boundary was assumed to be permeable, with boundary pore-water pressures equal to the hydrostatic value from the piezometer record in the earth flow mass (Case 2, Table 1). This assumption approximated a case where the shear zone is made up of a series of discontinuous lenses of fine-grained material, such as

Table 1. *Computed threshold pore water pressures.*

Water Year	Computed Threshold Pore-Water Pressure, psf	
	Case 1a	Case 1b and 2
1977	1,046–1,047	1,049–1,055
1978	1,046–1,053	1,048–1,058
1979	1,040	1,047–1,050
1980	1,043–1,050	1,044–1,051
1981	1,026–1,037	1,033–1,037
1982	1,033	1,038–1,042
1983	1,044–1,047	1,052–1,054
Average for all Years	1,043	1,047

Case 1a—10-in. thick shear zone with top drainage only, c_v = 0.01 ft²/day.
Case 1b—10-in. thick shear zone with a thin impermeable interface at the center and top and bottom drainage, c_v = 0.0045 ft²/day.
Case 2—10-in. thick shear zone with top and bottom drainage, c_v = 0.0045 ft²/day.

might be expected in a debris deposit like the earth flow. In this case it is assumed that hydrostatic pore-water pressures can be transmitted to the lower boundary of the shear zone by paths between the fine-grained lenses.

The coefficient of consolidation, c_v, can be determined from laboratory tests on shear-zone soil samples. We could not obtain such samples, but did obtain samples of fine-grained lenses from the toe of the earth flow near the elevation of the shear zone; c_v values ranged from 1×10^{-3} to 8×10^{-3} in.²/min (6×10^{-3} to 5×10^{-2} cm²/min). These values should be higher than the true shear zone value because deformation tends to orient fine soil particles and thereby reduces c_v.

Expected Model Results

Layer thickness, boundary condition, and coefficient of consolidation all control the rate at which pore-water pressures propagate into the shear zone. Determining any of these parameters exactly is impossible. However, data from the Lookout Creek earth flow do provide a good estimate of layer (shear zone) thickness based on borehole deformation, a reasonable range of boundary conditions based on piezometer readings and likely subsurface conditions, and at best, an order of magnitude estimate of the upper bound to c_v based on laboratory tests. Therefore, computation of shear zone pore-water pressures using the theory of consolidation will provide only a range of estimates, and not an accurate prediction. However, if the hypothesized mechanism of pore-water pressure propagation into and out of the shear zone is correct, then the pattern of predicted pore-water pressures must match the periods of earth flow movement; that is, pore-water pressures must rise above the threshold value as earth flow movement begins and drop below that value as movement stops. For the Lookout Creek earth flow, there are seven years of movement data that pore-water pressure predictions can be compared with. If a matching pattern exists for this long a period of record, then a substantial level of confirmation of the model exists.

The hypothesized mechanics will further be confirmed if the computed pore-water pressure is rising on the day movement begins and has not been exceeded before then. The piezometer readings show pore-water pressure falling on the day that movement began and/or higher values prior to the beginning of movement in some years; both trends are inconsistent with a factor of safety decreasing to 1.0 on the day movement begins.

We do not know the true boundary conditions on the shear zone. However, if the consolidation model is correct, then a reasonable match between estimated pore-water pressures and observed movement data should be obtainable for all the boundary conditions considered simply by adjusting c_v within the expected range. This can be illustrated by examining the equation for time factor, T, (dimensionless time) from the general solution to Equation 2 (Taylor, 1948):

$$T = \frac{c_v t}{H^2} \qquad \text{Eq. 3}$$

where: t = time
H = drainage path (layer thickness/number of permeable boundaries)

For a simple boundary condition (constant pore-water pressure after an instantaneous increase), a reduction in H by one-half, to simulate the difference between top drainage only and top and bottom drainage, must be accompanied by a reduction in c_v to one-quarter the original value, to give the same T. Equal T's will produce equal average nonequilibrium pore-water pressures versus time. Because the adjusted c_v is still within the order-of-magnitude range observed in the laboratory for fine-grained soil from the earth flow, none of the boundary conditions considered is likely to be ruled out. For a more complicated boundary condition (varying pore-water pressure), the case is more involved, but reasonable adjustment of c_v will have the same effect.

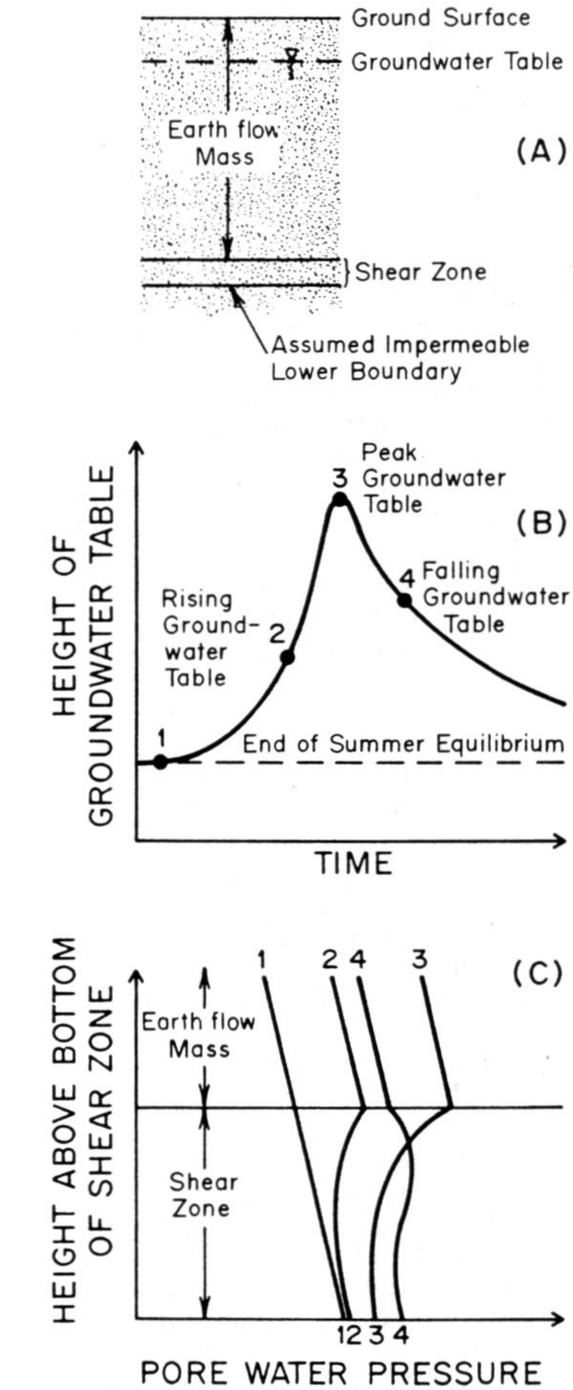

Figure 8. Schematic diagram of consolidation modeling for an impermeable lower boundary. (A) model soil profile, (B) groundwater response to precipitation, and (C) pore-water pressure profiles in the shear zone.

Actual Model Results

The boundary conditions previously described, a shear zone 10 in. (25.4 cm) thick, and a range of c_v values were used in an explicit finite-difference formulation of Equation 2 (Dunn et al., 1980) to determine the pore pressures in the shear zone of the Lookout Creek earth flow for WY's 1977–83.

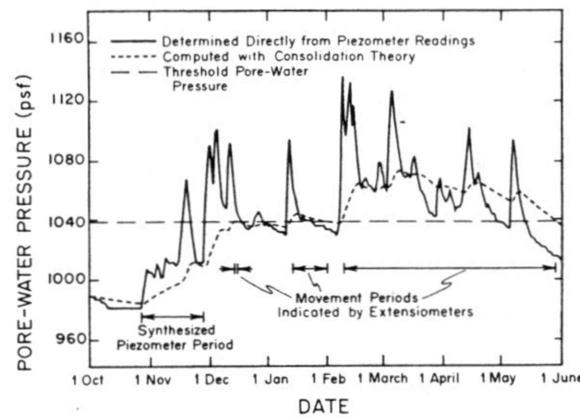

Figure 9. Pore-water pressures at the center of the shear zone determined directly from measured piezometer levels in the Lookout Creek earth flow, and computed with the Terzaghi consolidation theory for water year 1979; impermeable lower boundary assumed.

The finite-difference solution to Equation 2 shows that the pore-water pressures on the upper boundary of the shear zone are propagated through the shear zone over time. If the pore-water pressures on the boundary are greater than those in the shear zone, then pore water flows into the shear zone, and the pore-water pressures increase (Figure 8); if the pore-water pressures on the boundary are less than those in the shear zone, then the pore water flows out of the shear zone, and the pore-water pressures decrease. According to the Terzaghi theory of consolidation, a volume change must accompany the flow of pore water in and out of the shear zone; however, the magnitude of that change is small because of a low coefficient of compressibility and the rather modest stress change. The time lag between an increase in pore-water pressure in the earth flow and a corresponding increase in the shear zone explains why the earth flow may remain stationary at high piezometric levels in early fall and then start to move a few weeks later when piezometric levels have declined (Figure 9). Occasional gaps in the record of a few days to as much as 4 weeks (Figure 9) were not so large nor numerous that a reasonable record could not be synthesized based on the continuous precipitation record from near the site and the relationship between precipitation and piezometer reading.

If the hypothesis of partial drainage is correct, and the strength of the shear zone can be adequately described by friction alone, then the threshold pore-water pressure should be similar from year to year. Threshold pressures for WY's 1977–83 were estimated by selecting the computed pore-water pressure at the center of the shear zone on the day movement began, as indicated by extensiometer records (Table 1). The value at the center was considered representative because pore-water pressure in the shear zone varies from top to bottom. Threshold values are shown for up to 3 days because of the difficulty in determining the exact day on which movement began. Although estimated threshold pressures differ slightly for the 3 boundary condition cases examined (Table 1, average difference of 0.5 percent), adjusting c_v produced pore-water pressure patterns consistent with earth flow movement for all cases. The threshold pore-water pressure values for a given boundary condition are not constant, but the variation is not large. In terms of piezometric head, the variation shown in Table 1 is <0.5 ft (0.15 m), and the variation from plus to minus one standard deviation from the mean is <0.25 ft (.075 m). The relatively constant threshold value from year to year supports the partial-drainage hypothesis. Additionally, for each year, the estimated pore-water pressures on the day movement began were higher than on all previous days of that water year, and were increasing; these trends are consistent with a decreasing factor of safety.

The average threshold pore-water pressure corresponds to an increase in phreatic level of about 1.4 ft (0.4 m). This phreatic level, the depth to the failure surface, hillslope angle, and the unit weights previously presented give a back-calculated function angle of 14.9°.

INFLUENCE OF MANAGEMENT ACTIVITIES ON MOVEMENT

The preceding analysis indicates how the ground-water regime affects movement of the Lookout Creek earth flow. Forest management activities can influence ground water in two ways. First, skid roads and landings used for timber harvesting can alter surface and subsurface drainage patterns, thereby altering the ground-water regime. Second, the evapotranspiration rate of a forest is temporarily reduced after harvesting, increasing soil moisture and possibly, ground-water level.

Changes to drainage patterns of the earth flow can be minimized, if not entirely eliminated, by good logging practices; hence they will not be considered here. Evapotranspiration rates for mature forests in the Lookout Creek drainage have been found to be about 4 in. (10 cm) of water per month in July (Rothacher et al., 1967) and computed to be on the order of 2 in. (5 cm) per month in January (Waring, 1985). Though no data exist for the Lookout Creek drainage, Waring and others (1981) indicate that evapotranspiration rates for coniferous forests are reduced by two-thirds in summer and one-half in winter immediately after clearcut harvesting. The influence that changes of this relative magnitude have on ground water, and ultimately earth flow movement, is a function of the ground-water regime, including the surface and subsurface watershed that contributes ground water to the earth flow, the portion of the watershed experiencing reduced evapotranspiration from harvesting, and the time for evapotranspiration to return to preharvesting levels as a second-growth stand develops.

The ground-water regime within the Lookout Creek earth flow is complex, with water flowing alternately on and beneath the surface from one channel to another. The watershed area contributing ground water to the earth flow can only be determined by extensive field exploration and monitoring, which were beyond the scope of this project. The evapotranspiration recovery rate can only be determined through field monitoring in the western Cascade Mountains; this has been done for streamflow (Harr, 1983), but not directly for ground-water flow and piezometric level. Therefore, detailed modeling of ground-water flow in the earth flow currently is impossible. But the observed system response to rainfall can be used as the basis for assessing the likely effect of clearcut harvesting on the Lookout Creek earth flow.

During summer, when rainfall is minimal, piezometers and visual observations indicate that ground-water levels drop to a dry-season low, generally about 8 ft (2.4 m) below the ground surface at piezometer 1 but still at or above the ground surface in some depressions. Within 2 days of a typical large winter storm, the ground-water level at piezometer 1 rises 3 to 4 ft (0.9–1.2 m) above the dry-season base level as a result of rainfall and, presumably, subsurface flow an order of magnitude greater than that in the dry season; moreover, if there is little or no rainfall for 2 to 3 weeks after such a large storm, the ground-water level returns to within about 1 ft (0.3 m) of the dry-season low. These observations indicate that the earth flow can drain large amounts of precipitation rapidly and return piezometric levels in the earth flow to a base value.

Predictions of increased streamflow from clearcutting in the Lookout Creek drainage (Rothacher et al., 1967; Rothacher, 1970) indicate that reduced evapotranspiration the first 2 years after harvesting produces seasonal increases in runoff (Table 2). The impact of these increases on earth flow movement is a function of both the timing of the runoff and the magnitude of groundwater rise accompanying it. The increase in runoff after harvesting will be evenly distributed over time (Rothacher, 1970), except during the first 4 to 6 weeks in fall, when runoff may increase more during than between peak flows. The ground-water rise that accompanies a post-harvesting increase in runoff can be assessed by examining the increases in ground-water level associated with peak runoff events during the wet season.

An order-of-magnitude increase in streamflow is common during storms on small watersheds in the area of the Lookout Creek basin (U.S. Army Corps of Engineers, 1952). Ground-water peaks associated with these storms raise the ground-water level in the earth flow by as much as 3 ft (0.9 m). If a linear relationship between ground-water level and runoff is assumed, a 100-percent increase in runoff, like that expected in fall (Table 2), would raise the ground-water level 0.3 ft (0.1 m), which could initiate earth-flow movement earlier in fall and increase annual movement. We believe the increase will be modest, perhaps similar to the amount of movement during the first 2 weeks in fall (e.g., Figure 4). During winter, when earth flow movement is greatest, however, a 15- to 20-percent increase in runoff (Table 2) should only raise the ground-water level 0.04 ft (0.1 m). Because that increase is small (about 4 percent) in relation to the increase necessary to start movement, we believe the increase in movement will be small as well.

The limited potential for increased movement of the Lookout Creek earth flow can also be seen by comparing the records of movement and wet-season precipitation. From WY 1976–83, no trees were harvested upslope of the earth flow; hence evapotranspiration there must have been that of a mature forest. During this same period, wet-season precipitation commonly varied by 20 to 30 in. (50–75 cm) from year to year and, in one year, by 50 in. (125 cm). If evapotranspiration rate was relatively constant, then differences in precipitation must have appeared as differences in runoff. Runoff differences of 20 to 30 in. (50–75 cm) a year are somewhat

Table 2. *Predicted runoff increase after clearcutting in the Lookout Creek drainage (adapted from Rothacher et al., 1967; Rothacher, 1970).*

Season	Runoff Increase	
	Inches	Percent
Fall (October–November)	6–8	80–105
Winter (December–March)	7–9	15–20
Spring (April–June)	1–2	7–15
Summer (July–September)	1	60

greater than those predicted after clearcutting and would have occurred as storm peaks rather than a constant increase over time. This variation in precipitation and, presumably, runoff corresponded to a large percentage difference in earth flow movement, but absolute differences of only 3 to 6 in. (7.5–15 cm). Because these observed differences in movement are in part the result of storm peaks, and not of a constant increase over time, they must be considered an extreme upper bound to the difference in movement that could result from increased runoff after clearcutting.

This hypothesized potential for increased movement of the Lookout Creek earth flow is based on the extreme assumption of complete, one-time harvesting of the earth flow watershed and a rough correlation between runoff and ground-water response. However, such an extreme harvesting strategy is unlikely. Spacing harvesting over time will tend to reduce what appears to be an already low potential for increased movement. The rough correlation between runoff and ground-water response is reasonable, but determining the exact value of an increase in movement would require a detailed ground-water and evapotranspiration model of the earth flow and upslope watershed.

SUMMARY

The currently active area of the Lookout Creek earth flow, which shows direct evidence of movement over the past 80 years and indirect evidence of movement for much longer, consists of a relatively thin layer of slide debris moving on a basal shear zone within a thick debris deposit of uncertain origin. The shear zone apparently is composed of fine-grained soil that has a much lower shearing resistance than would be indicated by the gravelly to bouldery material in the earth flow mass. Earth flow movement is a general response to wet-season ground-water levels, but a direct cause and effect relationship can only be shown when the time rate of propagation of pore pressures into the less permeable shear zone is considered. A numerical solution to the Terzaghi theory of one-dimensional consolidation was used to estimate pore pressure in the shear zone.

The ability of the earth flow to drain rapidly to a base level that will not produce movement, indicates that a large increase in movement resulting from timber harvesting on the earth flow watershed is unlikely. However, an exact estimate of the potential for increased movement cannot be made without detailed data on regional ground-water flow and harvesting-related changes in evapotranspiration. Although the quick drainage response should be considered specific only to the Lookout Creek earth flow, with sufficient field data, the analysis presented here could be applied to other earth flows, providing a useful tool in forest management planning.

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